Hibot
DeepStar® 2025
Robotic Intervention During Outages NUF
FINAL REPORT

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October 6th, 2025

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1. Executive Summary

Hibot was awarded the reference project as a Phase III study under the DeepStar–Nippon Foundation program to extend the capabilities of the Float Arm robotic system beyond inspection toward light maintenance applications in offshore environments. The primary objective was the feasibility study and prototyping of fabric maintenance tools, specifically for surface preparation and coating/painting operations. The project built on the successful evaluations conducted in Phase II, which demonstrated the Float Arm's unique advantage in remotely accessing complex and confined geometries with minimal human exposure.

During this phase, the team focused on integrating a **Sponge-Jet® low-dust blasting system** for surface preparation and an **airless sprayer for coating application**. Laboratory and outdoor tests confirmed that the Float Arm could stably perform blasting and coating tasks on flat and curved targets while achieving surface finishes equivalent to near-white metal standards.

Several limitations were identified during testing. When operating above-horizontal angles, certain servomotors entered overload protection due to thrust forces, and hose choke points occasionally reduced abrasive flow. In coating trials, while uniform spray patterns and film consistency were achieved on small surfaces, the arm's length caused flexing during high-speed motion, leading to oscillations at the tip and reduced accuracy over longer strokes. This dynamic behavior is typical of long-reach manipulators and may be addressed through mechanical reinforcement—such as increasing structural rigidity or refining link geometry to dampen vibration—or through software improvements that optimize motion trajectories and maintain endpoint precision. In addition, the use of heavy two-component coatings presented operational challenges that limited continuous application efficiency.

Extensive laboratory and outdoor evaluations were conducted to replicate representative offshore geometries, environmental conditions, and loading scenarios. These tests verified the arm's stability under dynamic thrust, validated surface preparation and coating quality on both flat and curved specimens, and confirmed system performance in realistic operational setups. The results provided a solid technical foundation for future deployment studies, establishing the Float Arm's readiness for further validation at larger scale and in more complex field conditions.

To support operational feasibility, the robot base was redesigned into lighter modules below 20 kg each, enabling safer manual handling and improved stability on FPSOs. In parallel, new "snake-like" motion software and a real-time 3D depth-camera prototype were developed to improve navigation in confined spaces and enhance operator situational awareness.

Through this phase, hibot demonstrated the technical feasibility of robotic surface preparation and coating tasks, marking a significant step toward autonomous fabric maintenance. The additional improvements in portability and manipulability strengthen the Float Arm's readiness for offshore deployment and align with the DeepStar–Nippon Foundation vision of reducing human exposure and operational costs through safe, remotely operated robotic maintenance solutions.

2. Introduction

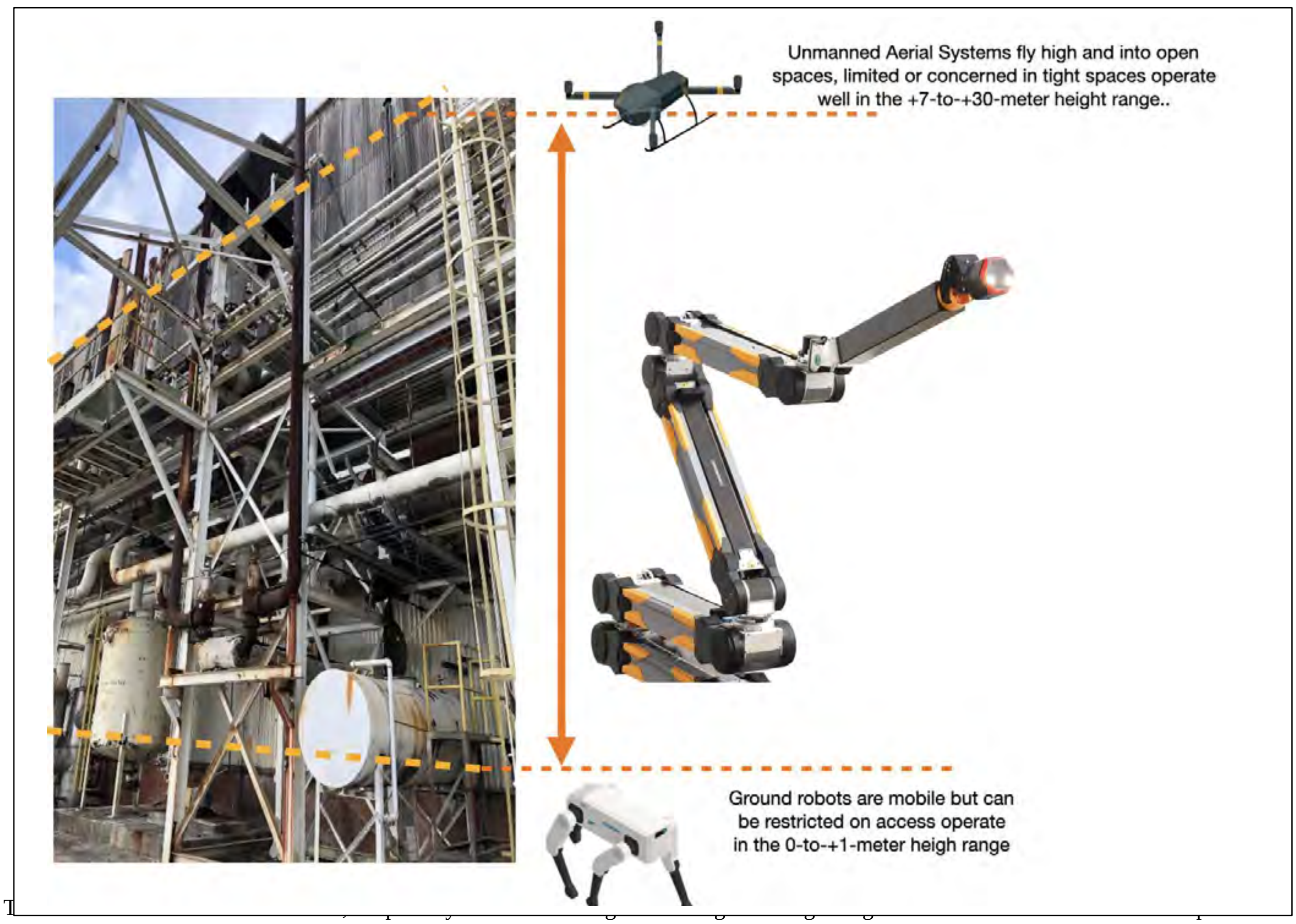
2.1. Scope

This document outlines activities, past and planned, meant to explore and demonstrate the potential contribution of the Float Arm, a product by Hibot Corporation, towards meeting the objectives of the DeepStar consortium. In this respect, the Float Arm is currently being tested for its usability in the inspection of difficult to access parts or congested zones of offshore oil and gas facilities.

The potential areas of application (considering the currently available integrated sensors) of the Float Arm in offshore facilities include the following forms of remote inspection:

- Visual inspection of pipelines on floating facilities to determine corrosion and other damage.
- Determination of the wall thickness of pipelines on floating facilities.
- External visual inspection of tanks on floating facilities to determine corrosion and other damage.
- Determination of tank wall thickness at parts of the tanks that are difficult to access.
- Tank entrance and internal visual inspection of tanks in semi-autonomous mode.

Evaluation and test criteria are outlined for the evaluation of the Float Arm.
Future possible applications will target maintenance, such as coating, cleaning, blasting but also inspection with different type of sensors
The image below depicts the workspace that can be addressed by the float arm in comparison with other robotic solutions.



2.2. Background

2.2.1. Offshore Inspection: Current Practice

The future of NUF facilities (Normally Unattended Facilities), is to decrease the number of people and heavy machineries that are needed on site. Normally when operations of inspection and maintenance occurs, teams of 20~30 people are taken to offshore platforms with heavy machines.

Inspections must be carried out with precise and regular schedules. During these times human operators are requested to climb and move among difficult structures, to take pictures, using ultrasonic sensors to measure wall metal thickness and look at possible problems. In fact, corrosions or cracks can cause issue in the offshore structure and even explosions.

The Float Arm is a long reach multi axis robot arm. To date it has been utilized to complete the following industrial inspections mainly at onshore location:

- The remote visual inspection of indoor and outdoor pipeline complexes at industrial complexes such as chemical plants, enabling high resolution imagery from elevated and difficult-to-access locations.
- The remote measurement of pipe and tank wall thicknesses in industrial complexes such as chemical plants.

2.3. Abbreviations

Abbreviation	**Meaning**
CUI	Corrosion under insulation
NUF	Normally unattended Facilities
PEC	Pulsed Eddy Current
UT (sensor)	Ultrasonic sensor
FPSO	Floating Production, Storage and Offloading System

2.4. Detailed of Work for Phase III

Based on the results of the previous phase tests, it was decided to focus on the following major points of exploration work and spot improvements:

1. Feasibility Study and Prototyping of Fabric Maintenance Tools mounted on the Float Arm
2. Mechanical design changes on the robot Base to Improve Portability
3. Software improvement for Faster and Easier Arm Manipulability in Confined Spaces

1. Feasibility Study and Prototyping of Fabric Maintenance Tools mounted on the Float Arm

Since phase 1, all the work was focused on tailoring the machine to be applicable for use in the offshore environment, however no focus had been given to evaluating tools that can be used for fabric maintenance.

Upon close collaboration with champions throughout Phase I and II, we have identified the potential application of a versatile arm such as Float Arm in conducting maintenance work. In this phase, we would like to study the applicability of Float Arm in fabric maintenance work such as surface preparation/cleaning, corrosion prevention or fireproofing assets through protective coating/painting, and rust removal.

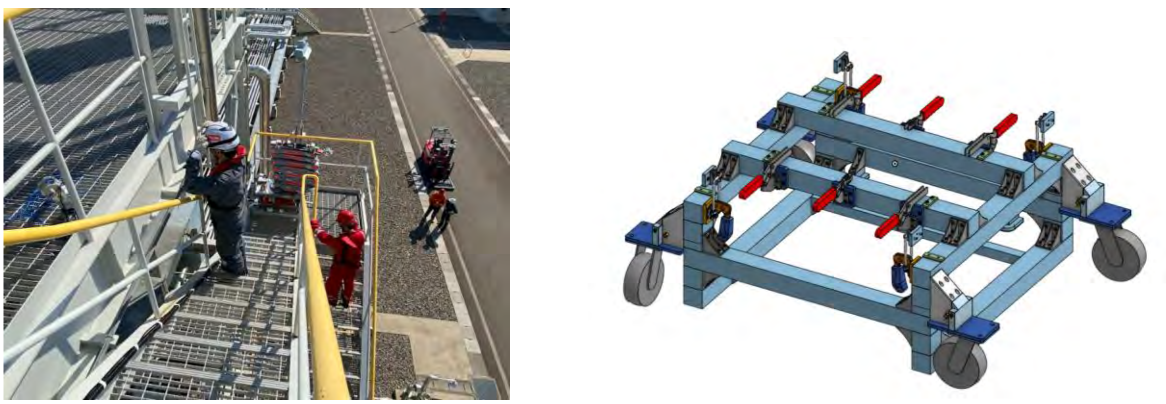
During the project, a feasibility study will be presented for each tool showing the merits and challenges involved in integration with the present version of Float Arm. The presented results shall then be treated as a reference in either (1) deployment of the process in actual field operations in case integration is possible, or (2) considering future work that might be necessary on the robot, tools, or processes in case there are gaps.

2. Mechanical design changes on the robot base to Improve Portability

In Phase II, a mobile frame was developed that presented several key improvements such as (1) application of *stowable* caster modules that enabled transport between operation locations, (2) redesigning the Base Unit to be more compact and attachable using toggle clamps that reduced assembly time, and (3) clearance to slot in forklift during transport or operation.

However, few issues have been identified during the use of this design in actual field tests.

- First, the base frame is 50 kilograms, which makes it infeasible to be transported by operators on stairs while satisfying “three points of contact”.

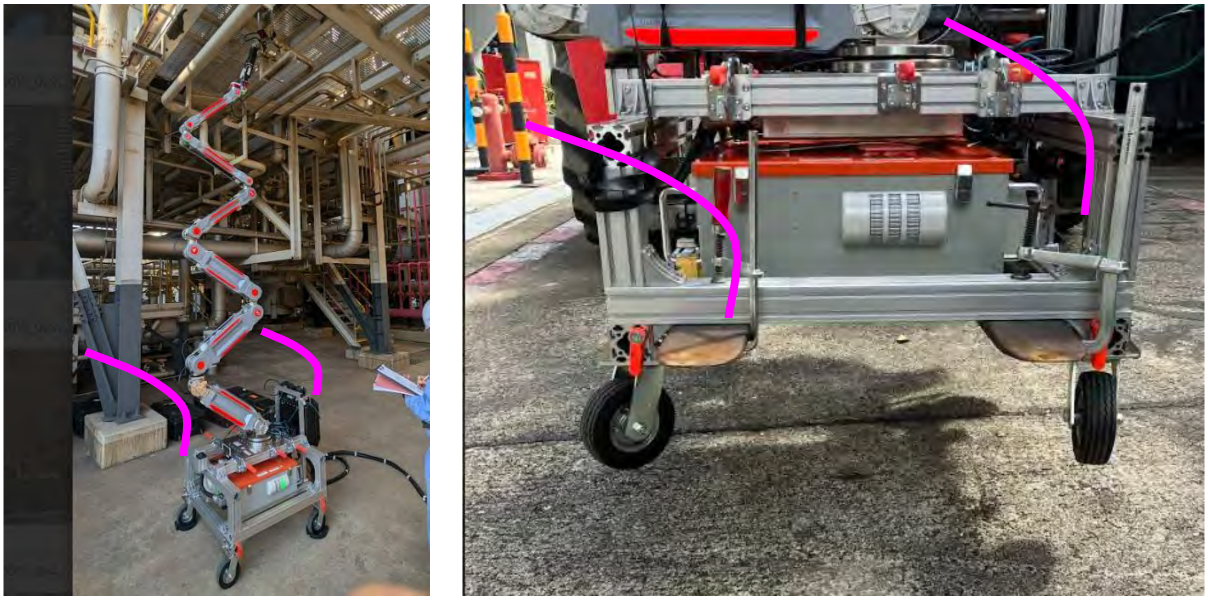


Difficulty in setting up the machine when bringing the base frame on top of stairs

- Second, the frame’s center of gravity is now higher due to the positioning of the base above the sub-box, making it easy to topple over when units are stretched 1.3-1.5m away from the base.

The aim in this project phase is to redesign the base part of the robot to counter the usability and safety issue. In particular, the new design should focus on satisfying key requirements:

- Shall be separable into modules, each with 20Kg or less. By doing so, operators will be able to transport parts of the frame by hand on stairs while satisfying the three points of contact. Re-assembly shall be almost instant (< 10secs) and need not require special tools to do so.
- Shall be stable when being transported and operated in a standalone way and have closed slots for forklift



(Right) Base starts to topple when units are stretched 1.3-1.5m away from the base.
(Left) Risk of rotation and falling on the side when the robot is unclamped when on a forklift.

3. Software improvement for Faster and Easier Arm Manipulability in Confined Spaces

Several software improvements were made in Phase II, such as manway detection and automatic trajectory definition for use in entering tank assets, and removal of part of the robot from the point cloud data to make the user experience smoother and faster.

Currently, the float arm is mainly operated using the Inverse Kinematics process. This requires the operator to dictate the direction in which the tip of the robot should be moved translationally (up/down, left/right, forward/backward), or rotationally (roll/pitch/yaw), and leaves the controls of each of the joints to the software. However, one shortcoming of this method is that the software might have to move several of the bottom units to produce the commanded motion of the tip, making the robot vulnerable to colliding with the environment especially when parts of the robot are in between tight spaces, which are prevalent in offshore assets.

The development of a “snake-like” motion software would make it possible for the robot to enter and exit a confined space by each of the links following a curved path, making it easier for operators to operate in these tight environments.

Another planned improvement is to evaluate the feasibility of integrating a real-time 3D sensor for live environmental mapping and to develop a prototype if proven viable. Currently, the robot captures static 'snapshots' of its surroundings, updating its model only when it stops to take another scan. A real-time 3D sensor would provide continuous updates, giving operators a more accurate and dynamic understanding of the environment—particularly in scenarios where the robot is out of sight. Additionally, real-time mapping could help identify potential collisions, enhancing operational safety and efficiency.

3. Findings and Results

3.1. Feasibility Study and Prototyping of Fabric Maintenance Tools mounted on the Float Arm

In the midterm report presented last November 2024, we presented several potential solutions to address the problem of surface preparation and coating. We summarize the solutions in the following table.

Table: Presentation of various tools used in surface preparation and coating in current practices

Category	BLASTING	COATING	POWER TOOLS		LASER
Tool	SpongeJet	Graco Airless Spray	Orbital Sander	Air Turbine Tools	GC Laser Systems
Image					
Application	Cleaning, Rust Removal, Surface Preparation	Painting, Fireproofing, Rustproofing	Rust Removal, Polishing		Rust Removal, Cleaning
Anchor Pattern	Yes	not applicable	No	No	????
Tip Recoil	Force: 2Kgf min countertorque: none	Force: none countertorque: none	Force: max 0.9Kgf countertorque: none	Force: ? countertorque: ?	Force: zero countertorque: zero
Nozzle / Tip Weight	1 Kg	< 0.3g	1.27 Kg	0.23 Kg	3 Kg
Hosing	Required	Required	No	No	
Overblast / Overcoat	Medium	High	None	None	None
Operating Supply	Pneumatic	Electric / Pneumatic	Electric	Pneumatic	Electric
Required Control Precision	Medium	Medium	Low	Low	High
Price Point		$$$	$	$	$$$$$
Operator Training	Minimal		None	None	

Selecting the tools for this project phase

With the several technical (tip control, payload consideration, tubing, data integration, etc.) and non-technical (operator, tool vendor considerations, logistics) factors affecting the integration, we have decided to focus on two main tooling among the list: **(1) sponge blasting** for surface preparation, and **(2) airless sprayer** for painting and coating, for the reasons of the ease of tip control, mechanical integration, logistical requirements such as device procurements, operator availability, and vendor communication.

Studies on Applicable Standards on Surface Preparation and Coating

Furthermore, we also have investigated different international and regional standards on surface preparation and coating. The following table (c/o INPEX) indicates the following standards with which the development efforts have been referred to:

Table: Standards referred to during developments as provided by INPEX

Area	Standard Ref.	Surface Preparation	Basic Requirement: Surface Preparation	Applying Coating	Basic Requirement: Applying Coating
Japan	JIS Z 2301 (eq. to ISO 8501-1) JIS Z 2304(eq. to ISO 8504-2) SSPC-SP	JIS Z 2301 JIS Z 2304 SSPC-SP 5/NACE No.1 SSPC-SP 10/NACE No.2	- The status of rust and the level of surface preparation is defined by JIS Z 2301 - The level of rust removal by blast treatment is defined by JIS Z 2304 - The standards of the Society for Protective Coatings (SSPC) are referred to as required	JIS K 5659 JIS K 5660 ISO 12944	- Coating method, drying conditions are defined in JIS K 5659 - Coating thickness is determined by JIS K 5660 - The entire corrosion protection coating system is specified in ISO 12944
U.S.	SSPC ASTM NACE	SSPC-SP 5/NACE No.1 SSPC-SP 10/NACE No.2	- Surface cleanliness levels are determined based on project specifications and environmental conditions	ASTM D7124 NACE SP0178	- The planning of coating operations, mix formulation, coating equipment, application method, and drying conditions are properly managed - The coating Inspector is qualified based on NACE SP0178
EU	ISO 8501 ISO 8504 ISO 12944	ISO 8501-1 ISO 8504-2	- Rust condition and degree of surface preparation are specified in ISO 8501-1 - The degree of rust removal by blasting is defined in ISO 8504-2	ISO 12944	- The corrosion protection coating system for steel structures is specified in ISO 12944
Australia	AS/NZS 1580 AS/NZS 2311	AS/NZS 1580.4 AS/NZS 1580.5	- Rust removal on steel surfaces by blast cleaning complies with AS/NZS 1580.4 - Rust removal on steel surfaces by manual and power tools complies with AS/NZS 1580.5	AS/NZS 2311	- Paint application complies with AS/NZS 2311

Furthermore, we present as a result of our study a proposed process map of surface preparation and coating. We realized that it is **paramount to consider the whole process** surrounding the targeted application of surface preparation and coating in order to make nuanced design decisions on the integration of the tools.

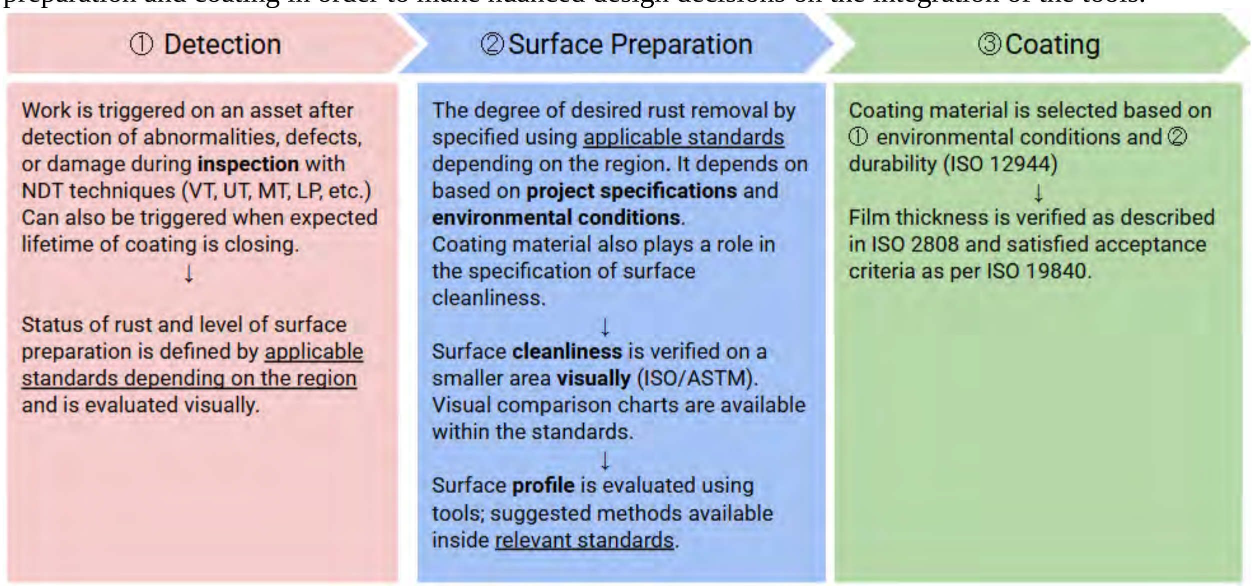


Figure: Fabric Maintenance Workflow

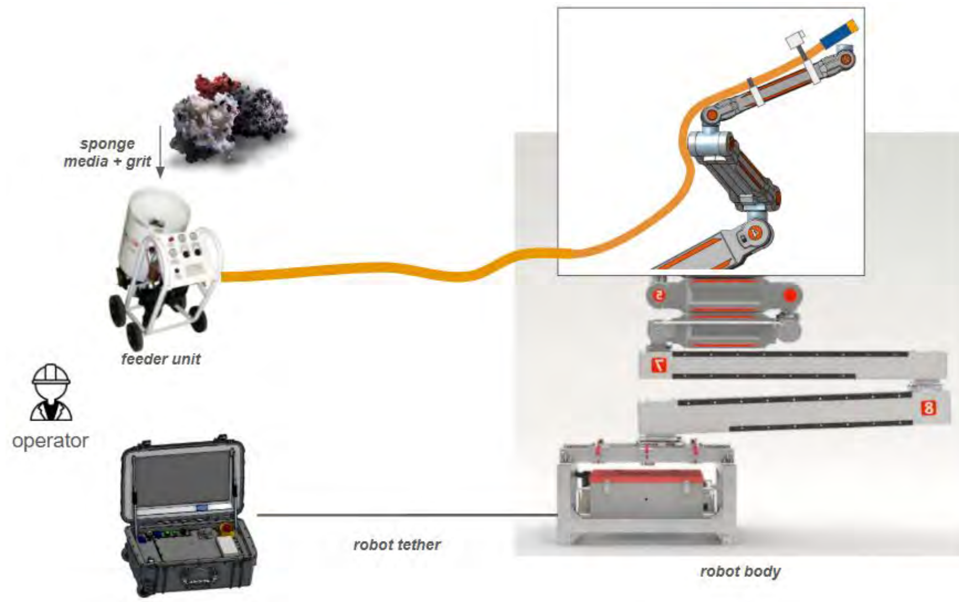
3.1.1. Mechanical Integration of the Sponge Blasting for Surface Preparation

The team has done a mechanical integration of the surface preparation solution SpongeJet. It is a low-dust, abrasive blasting technology that uses composite abrasive particles encased in a soft, sponge-like material. It is a surface preparation method designed to clean and profile surfaces with reduced dust generation and environmental impact compared to traditional abrasive blasting techniques.

The solution is chosen because of the premise that the sponge material is much lighter than other abrasive materials such as grit, which would require lower payload and weaker recoil force.

System Configuration

The system is configured as follows: the blasting hose is tied to the topmost unit, with the other end of the blasting hose connected to the feeder unit. The feeder unit will be located close to the operator control unit.



During the design phase, a critical decision involved the selection of the appropriate hose type for the system. Two primary options were under consideration: the black hose and the brown hose. After careful evaluation, the brown hose was ultimately chosen due to several key advantages.

Primarily, the brown hose offered a significant weight reduction, being 30% lighter per foot compared to the black hose. This reduction in weight directly translates to easier handling and potentially lower structural stress on the overall system. Furthermore, the brown hose demonstrated a superior ability to accommodate a smaller turning radius. This flexibility is crucial for navigating complex layouts and potentially reducing the number of fittings required, which can minimize potential leak points and simplify installation.

However, these benefits do come with specific trade-offs, as highlighted by the vendor. The lighter and softer composition of the brown hose, while contributing to its flexibility, also increases the likelihood of "choke points" forming along the path of the grit. Choke points can disrupt the flow of material, potentially leading to blockages, reduced efficiency, and increased maintenance. Additionally, the vendor indicated that the overall lifetime of the brown hose would be shorter compared to the more robust black hose. This shorter lifespan implies a need for more frequent replacements, which could impact operational costs and require more proactive maintenance scheduling. Therefore, while the brown hose offers immediate advantages in weight and maneuverability, the potential for choke points and a reduced service life are important considerations for long-term operational planning and maintenance strategies.

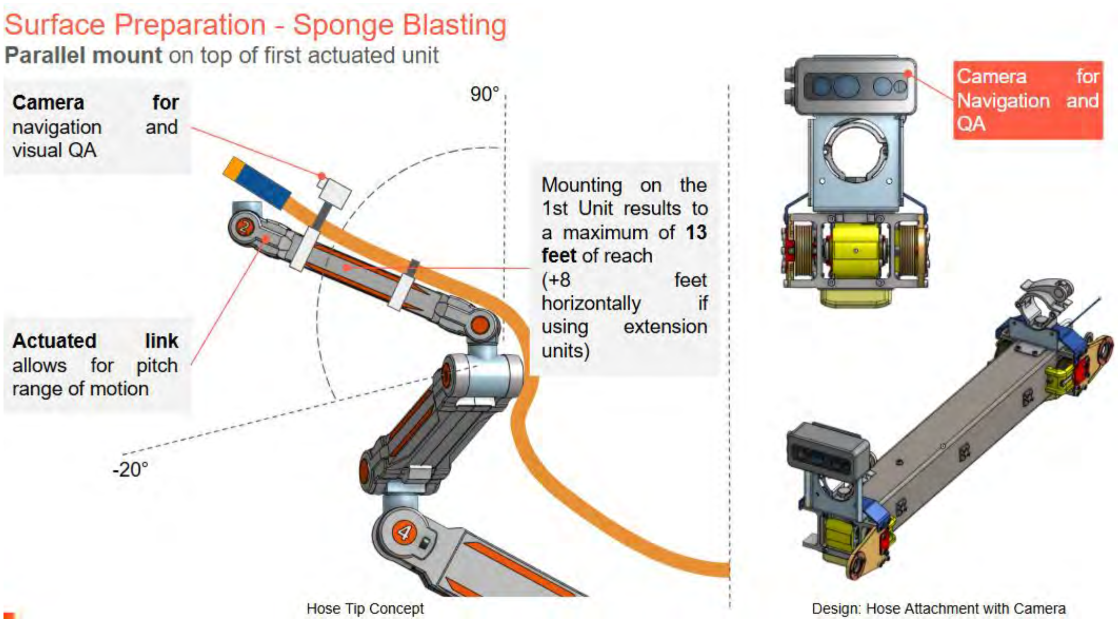
	Black Hose	**Brown Hose**
Cable Weight	1.5 lbs / ft	1 lb / ft
Outer Diameter	1.9” O.D.	1.5” O.D.
Bending Radius	18”	12”

The #6 nozzle is compatible to both brown hoses

Mount Design

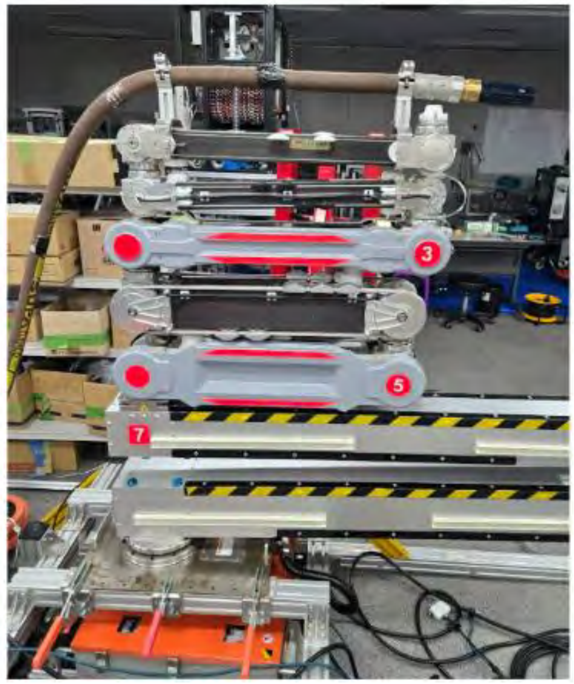
The following illustration shows the concept of mounting the hose on top of the first unit. This design has the following key features:

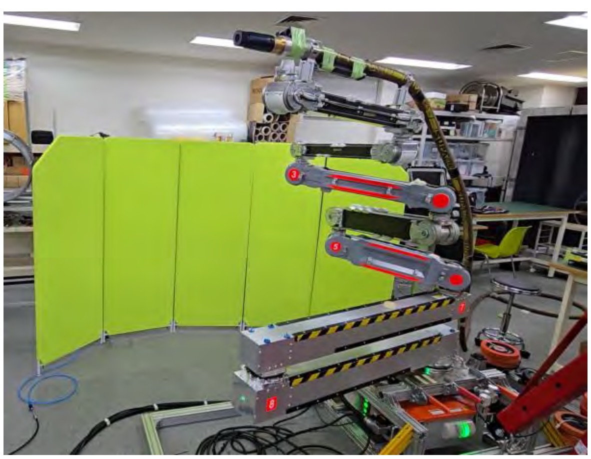
Item	Details
Sensing	Availability of an **hi-resolution (1080p) camera** with **3D depth sensing** for navigation that enables us to operate remotely without direct line-of-site with the robot, can also be used for pre-quality assurance
Reach and Manipulability	Actuated link on both Yaw and Pitch direction that would allow full coverage on a pipe
Hose Mounting	Mounting on top of the 1st link (Unit 1) using Quick-Release clamp
Reach	Up to 13 feet (up to 21 feet when using horizontal extension units)



Hose Fitting and Motion Tests in Laboratory Setting

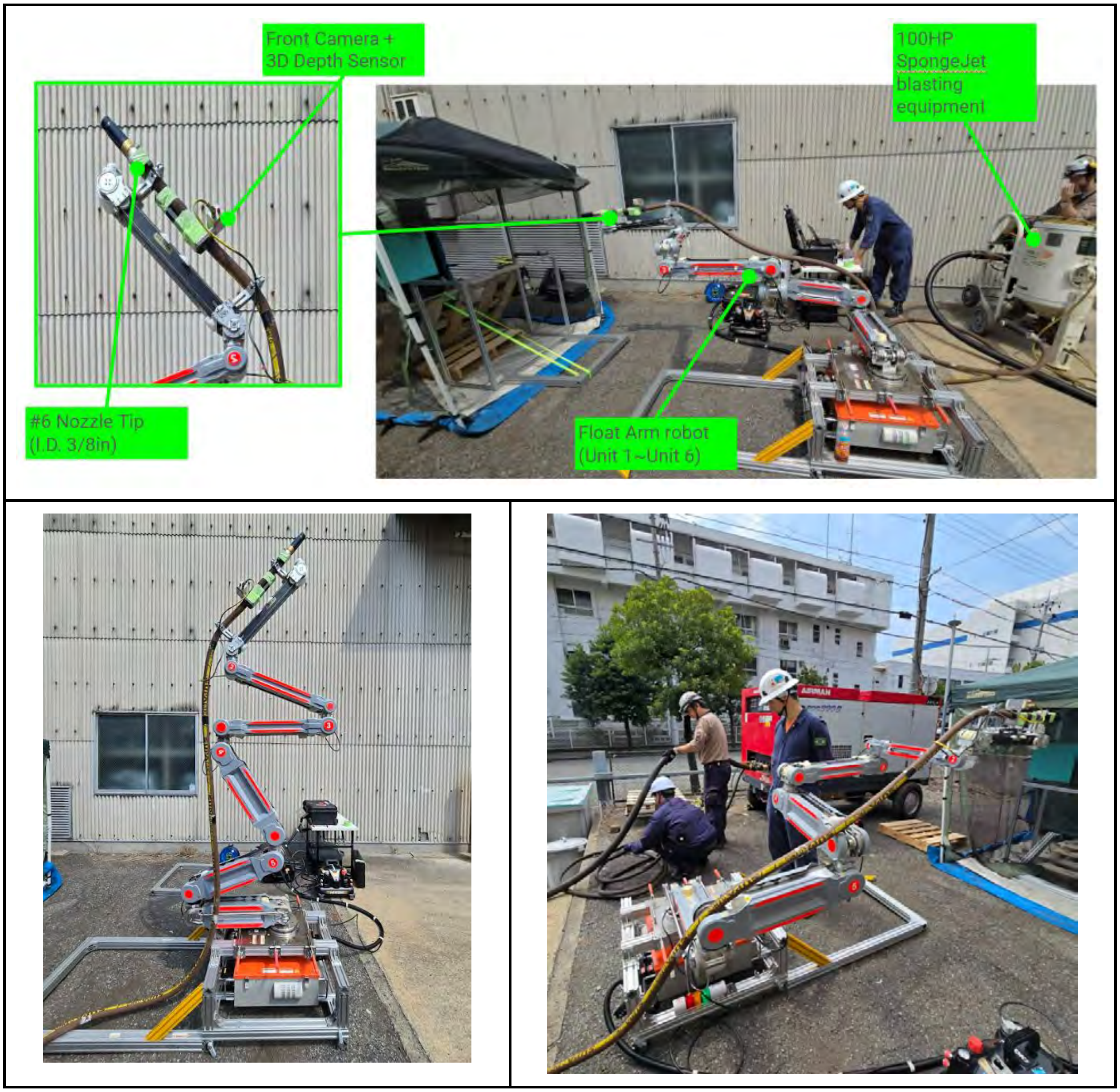
The following photos show the mounting and fitting of the hose on the actual robot in the laboratory setting.





Outdoor Test at Hyogo, Japan

The team conducted an outdoor test of the hose-mounted robot with the hose connected to the feeder unit with the intent to (1) verify the capability of the arm to withstand the thrust caused by the blast, and (2) test the manipulability of the arm with the hose mounted, and (3) conduct surface preparation work on test plates and pipes and evaluate surface cleanliness.



Outdoor Test Set-up

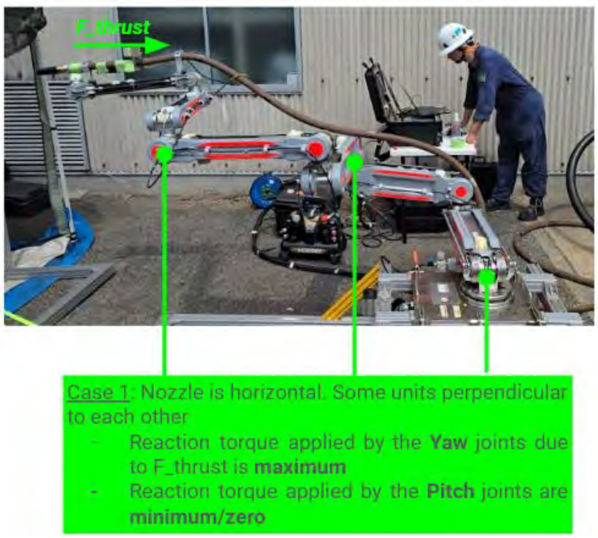
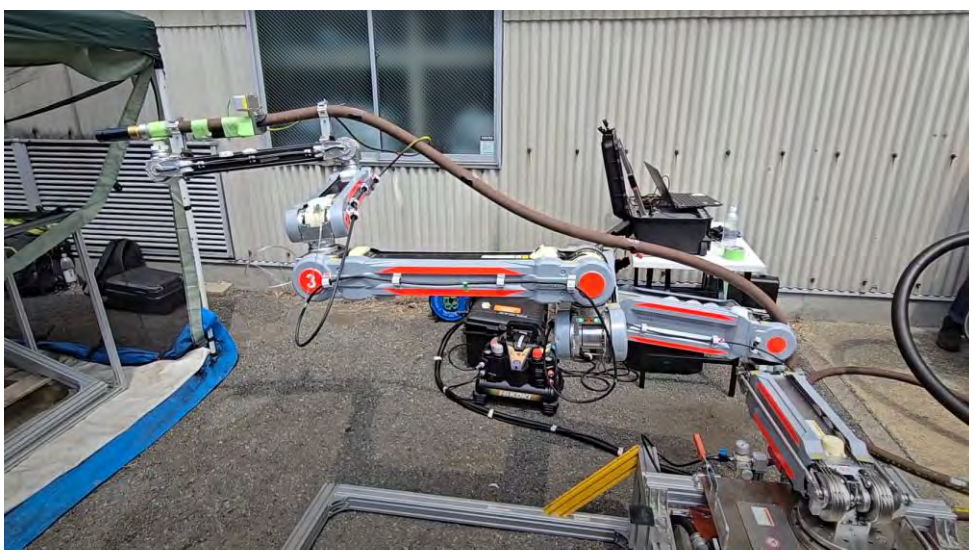
TEST RESULTS

1. Response of arm on thrust without abrasive material

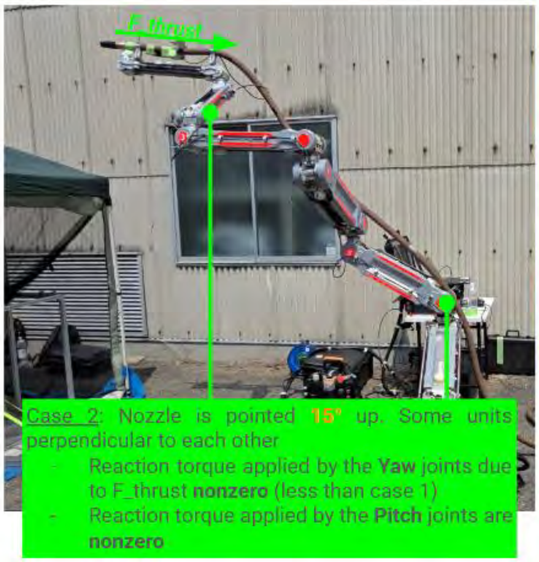
In this test, we wanted to see what is the effect of the thrust alone on the arm for varying positions. We mainly did the test for three positions - (1) Nozzle is Horizontal, (2) Nozzle is pointed 15° up, and (3) Nozzle is pointed up 40° up. The horizontal position test case (1) is added in order to test if the servomotors of the yaw joints can withstand the thrust, whereas cases (2) and (3) are added to see in what degree the pitch joints can withstand the thrust.

For this purpose, since the thrust force is coming mainly from the air flow coming out of the nozzle, we did not need to use sponge media. In all tests, the feeder unit pressure is gradually increased up to the standard working blast pressure of 80 KPa.

1.1. Case 1 : Nozzle is Horizontal

Test Condition	**Nozzle Position**. The nozzle is pointed horizontally to the ground. Units are aligned perpendicular to one another **Feeder Unit.** 80 KPa, no sponge media
	
	
Result: The arm was **able to withstand** the thrust for at least 1 minute without problems in the servomotors.	

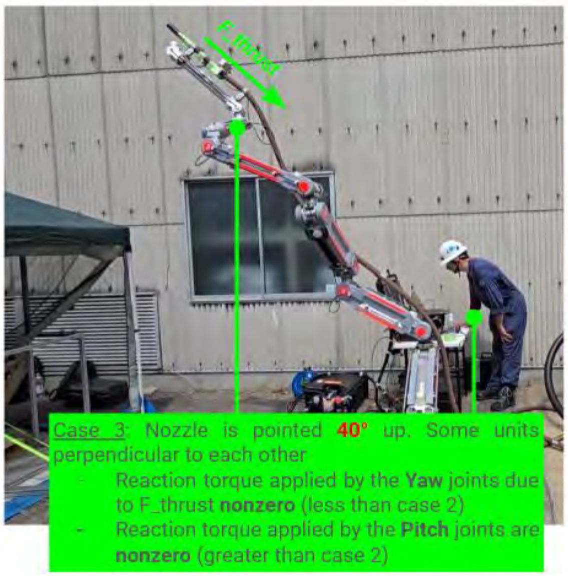
1.2. Case 2: Nozzle is pointed 15° up

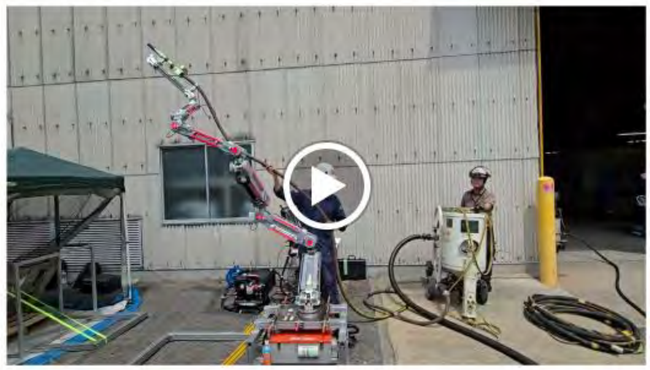
<table>
<tr><td>Test Condition</td><td>Nozzle Position. The nozzle is pointed 15° up with respect to the horizontal. Units are pitched up 15° with respect to the horizontal.
Feeder Unit. 80 KPa, no sponge media</td></tr>
<tr><td colspan="2">

</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Result: The arm was able to withstand the thrust for at least 1 minute without problems in the servomotors.</td></tr>
</table>

1.3. Case 3: Nozzle is pointed 40° up

Test Condition	**Nozzle Position**. The nozzle is pointed 40° up with respect to the horizonta. Units are pitched up **15°** with respect to the horizontal. **Feeder Unit.** 80 KPa, no sponge media





Result: After pressurizing the system for 5 seconds, the Unit 2 goes to overloaded state (overcurrent protection mode).

Discussion

A critical limitation was identified within the arm servomotors, specifically when the blasting hose was oriented above the horizontal plane. The arm demonstrated an ability to sustain a pitching up thrust of 15 degrees without issue. However, when subjected to a 40-degree pitching up thrust, the arm's capacity was exceeded, leading to failure. This observation strongly suggests that the vertical thrusting force, which acts as a payload on the arm, surpassed the current operational limits of the servomotors.

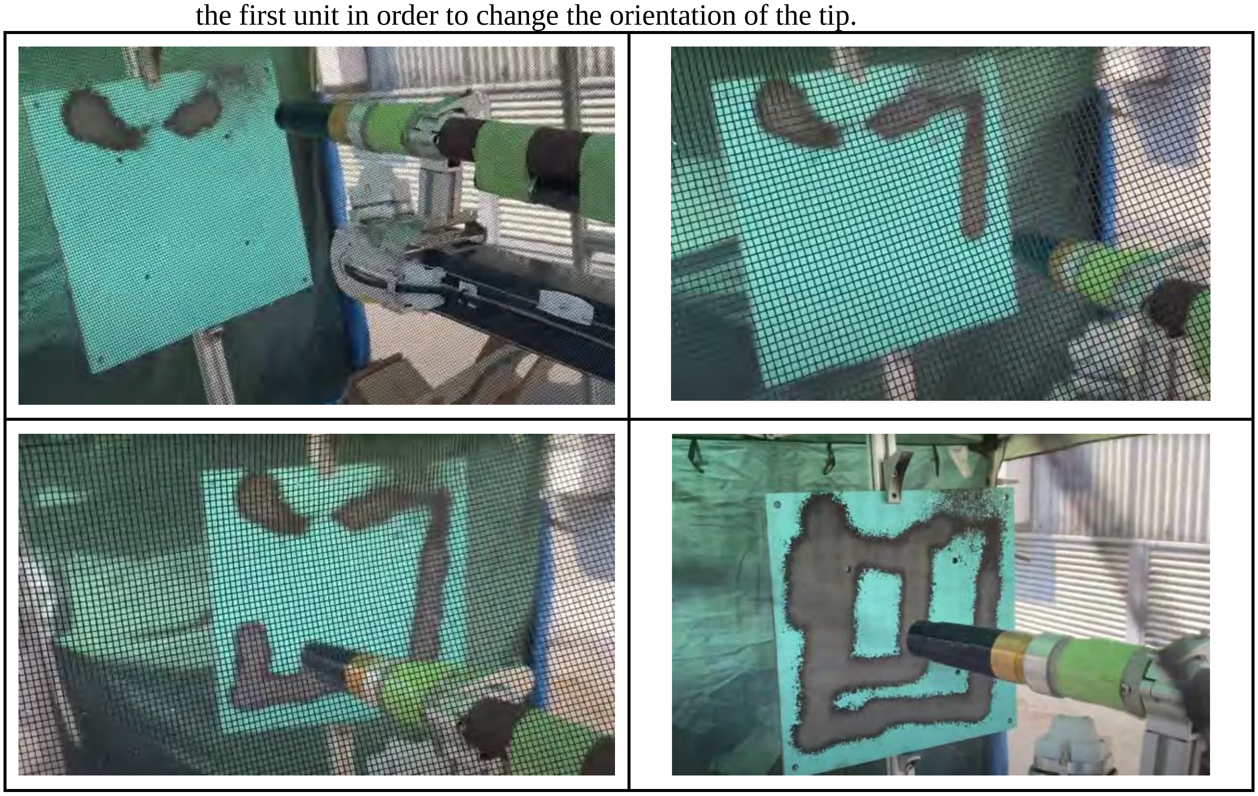
Further comprehensive testing is necessary to accurately determine the precise threshold at which this failure occurs. These additional tests will focus on pinpointing the exact limit between the successfully sustained 15-degree thrust and the failed 40-degree thrust, allowing for a more accurate assessment of the arm's true capacity and guiding future design modifications.

Moreover, to gain a precise understanding of the robotic arm's performance, a further test can be conducted. This experiment would be designed to quantitatively determine the exact relationship between the magnitude of the thrusting force exerted by the arm and its various poses (i.e., its spatial configuration, including joint angles and end-effector position and orientation).

2. Blasting Test

2.1. Blasting Test on a Flat Plate

We also conducted a test in which the blasting hose is oriented close to horizontal position. The blasting hose is pointing directly at the flat surface, while the operator is panning and pitching the first unit in order to change the orientation of the tip.



Blasting result: Flat Plate

2.2. Test on a 4” pipe with 6mm scaling

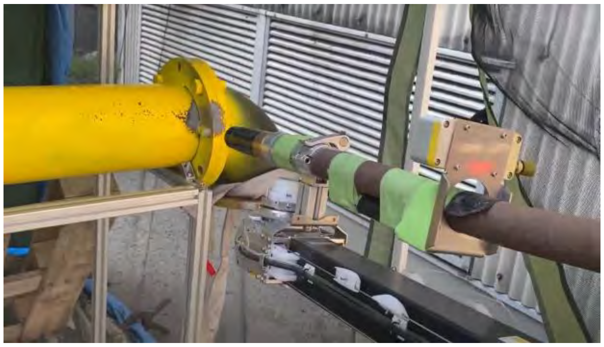
Furthermore, we also conducted a test on a 4” pipe with a 6mm scaling. This test is added since curvatures expose non-equidistant aiming distance between the nozzle tip and the pipe when blasting from a fixed point, which effectively reduces the abrasive impact of the grit.

Blasting result: 4” Pipe with 6mm Scaling

2.3. Test on a 6”, 0.5m long pipe with Paint

In addition to our other evaluations, we performed a crucial test on a 0.5-meter-long, 6-inch diameter pipe that had been painted. The primary objective of this specific test was to observe the dynamic characteristics and behavior of the robotic arm when more than one of its links was required to operate simultaneously.

This multi-link operation is a critical aspect of the arm's functionality in complex environments, and understanding its performance under such conditions provides valuable insights into its overall stability, precision, and efficiency. The painted surface of the pipe was also a deliberate choice, intended to simulate real-world conditions where variations in surface texture and friction necessitates proper control of the blasting tip to get a clean finish. This test allowed us to gather data on how the arm compensates for these factors and maintains its intended trajectory and grip during intricate maneuvers.




Results and Discussion

1. Blasting Feasibility for Small Spot Areas:

   For test cases involving spot areas with dimensions less than 20cm x 20cm, the current robotic arm configuration demonstrates the feasibility of conducting blasting operations. By solely manipulating the first link of the arm, it is possible to achieve a clean finish that complies with at least near-white metal standards (SSPC SP-10). This can be accomplished without overloading the arm's servomotors, indicating efficient and controlled operation for these specific scenarios.

2. Potential Overload for Above-Horizontal Pointing

   A potential issue has been identified when the robotic arm is required to point its tip above the horizontal plane. There is a discernible possibility that at least one of the unit's servomotors could become overloaded under such conditions. This suggests a limitation in the arm's current design or power management for operations requiring a high elevation or specific angular positioning, and further investigation or calibration may be necessary to mitigate this risk.

3. Importance of Perpendicular Aim for Hose

   The 4-inch pipe test results revealed a cleaner finish near the horizontally oriented centerline, but the ends showed less cleanliness.

   This highlights the critical importance of perpendicularly aiming the blasting hose at the target surface for optimal results, particularly with small outer diameter curved pipes. Precise aiming guarantees consistent and effective grit application, preventing uneven blasting, material waste, and potential substrate damage. Deviating from perpendicularity can reduce efficacy and lead to inconsistent surface preparation.

4. Achievability of Anchor Profile

The system has demonstrated its capability to achieve the expected anchor profile of 60-100 microns using the specified grit and feeder system. This is a critical factor for ensuring proper adhesion of subsequent coatings or treatments. The consistent attainment of this anchor profile validates the effectiveness of the chosen grit, feeder, and blasting parameters in preparing surfaces to the required specifications.

Technical Limitations

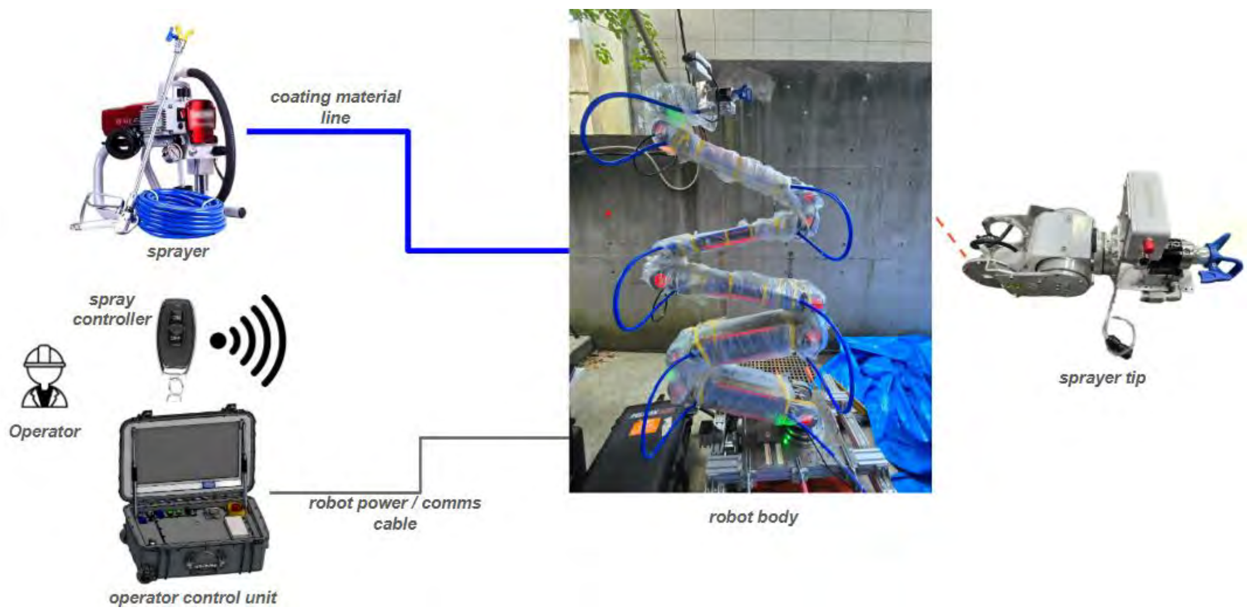
Issue	Possible Solution
The arm is having a difficulty supporting the weight of the hose at some poses	Consider adding a passive hanger arm for the hose, which is an extra component. Alternatively, make the servo-motors more powerful.
Hose-bearing unit 1 cannot make a pitch angle more than 20 degrees with the horizontal. The servomotors are not powerful enough to hold the thrust at an angle. However they can hold the hose when the tip is horizontal. This is suitable for flat/almost flat surfaces such as storage tank walls.	Make the servomotors more powerful to be able to support the thrust caused by the blasting tip
The amount of remaining stains and shadows on the surface depends on **aiming angle.** It is important to maintain 90° aim towards the surface to ensure near-white (SP-10) or white-metal (SP-5) standard	By improving the servomotors, it will be easier to maintain
Pre-planning the motion still takes a significant amount of operational time	More automation is necessary
The motion is not synchronized with the feeder unit; activation of blasting action is done manually	Need to add a way how to synchronize the blasting action with the motion of the robot by software

3.1.2. Mechanical Integration of a Sprayer Tip for Painting & Coating Application

During the selection of coating equipment for the Float Arm, an airless nozzle solution was chosen over conventional air spray systems because airless nozzles atomize the coating using hydraulic pressure instead of compressed air at the tip. This eliminates the counterforce typically generated by compressed air.

System Configuration

The sprayer system consists of four main parts - (1) sprayer tip, (2) sprayer, (3) robot controller, and (4) robot body



Sprayer Tip. The sprayer tip is the part where the coating/paint material comes out. It is made so that the nozzle action can be activated electronically. This makes it possible to synchronize the motion of the robot with spray action eventually.

Sprayer. The sprayer can be any off-the-shelf airless sprayer. For example, *Graco magnum X7*. The sprayer can be chosen depending on the particular coating requirements (e.g. rustproofing, coating, painting).

In the prototype version of the design, the sprayer action will be activated manually by the operator using a FOB key. In the higher TRLs this activation will be directly programmable using the controller software.

Robot Body: The snake-like robot that carries the sprayer gun with the nozzle tip. The robot with the coating tip has a reach of up to 13ft vertical, up to 21ft horizontal (with extension links attached) and has a total of up to 18 degrees of freedom, making it able to navigate elevated and congested areas, and can target areas of arbitrary geometry.

Tip Design

To accelerate development, we leveraged an existing carrier module capable of supporting up to 4.4 lbs of payload for the sprayer tip. This carrier module has been used in the past to carry other payloads such as Pulsed Eddy Current (PEC) Sensor for pipe screening of corrosions under insulation (CUI).

The sprayer end connects directly to unit 1, providing a reach of up to 15 feet vertically from the robot base, and up to 22 feet horizontally from the robot base. The tip features three degrees of freedom—yaw, pitch, and roll—allowing for motor-driven adjustments to ensure even spray distribution from the orifice.

For navigation, a visual and real-time depth-sensing module was integrated at the rear of the sprayer. Additionally, an electronic circuit has been incorporated to enable remote spray activation via a FOB key.

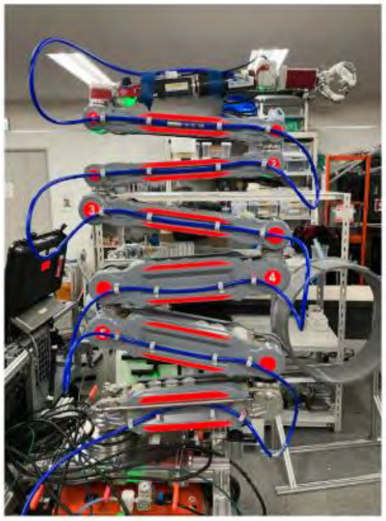
Sprayer End-Effector, Side View

Front View

Hose Fitting and Body Cover

The hose is attached to the side cover clamps of the robots. While the hose fits the attachment, the clamps seem to be a bit fragile to hold the hose.

It was previously thought that since the hose will be filled with pressurized coating material, the hose might get stiff and constraint the robot. However, pressurizing the hose with water close to the nominal pressure levels used in actual coating work, we have seen that the pressurization seems to not cause any problems. We were also able to check that the arm is able to move unconstrained even if the hose is pressurized had shown that the hose does not change in stiffness



Hose fitting on the robot

Attachment clamps seem too fragile to hold the hose

Motion test with the hose

To protect the robot arm from paint, we covered it with plastic. The camera lenses were shielded with PVC protection sheets to ensure visibility while preventing overspray.

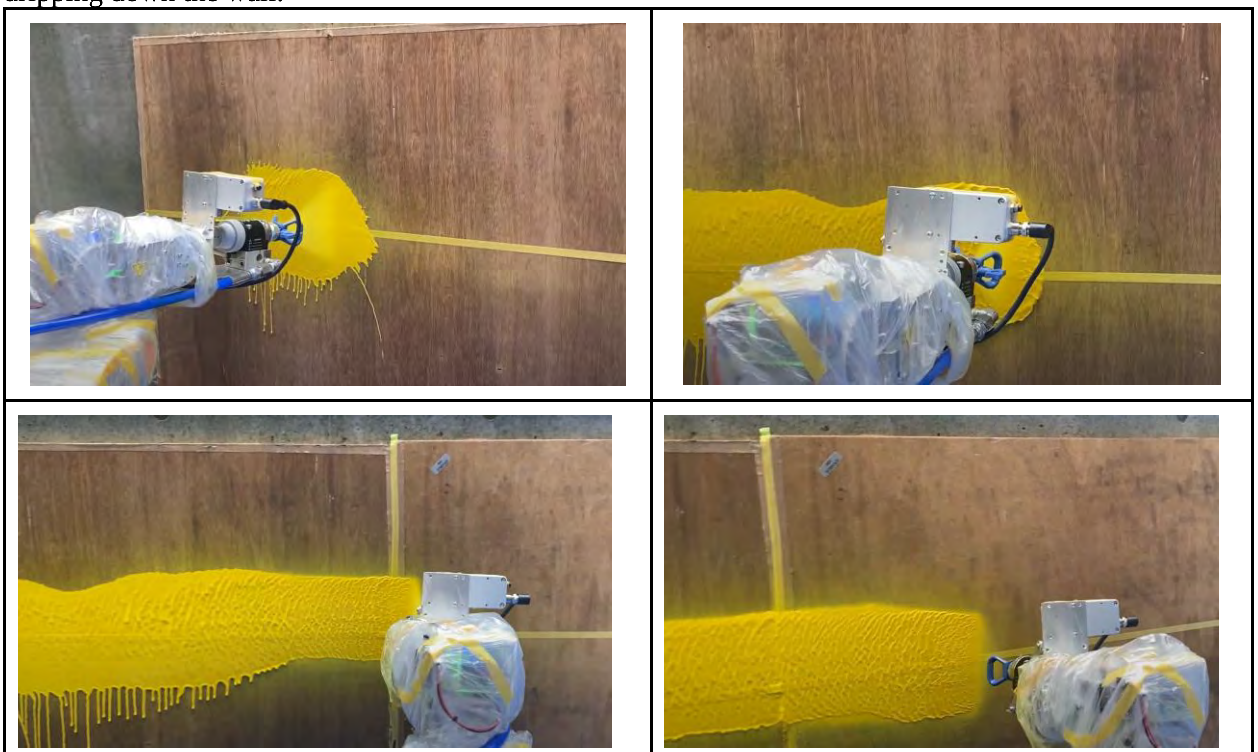
Test Results

We conducted painting tests on two geometries - (1) flat wall, and (2) a 6" pipe. During the tests, we identified and tuned several key parameters that has the most impact on the quality of the paint:

- Robot speed. The speed dictates the volume of paint expelled on the section of the target surface.

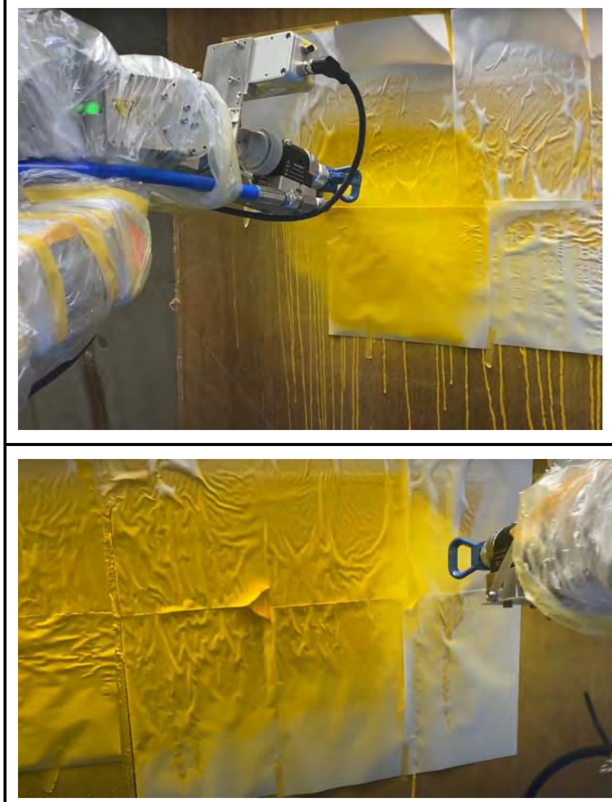
- Repeatability. The paint workflow involves a pre-planning step at the beginning where the path is recorded. The path is then replayed and synchronized with the spray action.
- Pressure. The amount of pressure controls the flow of liquid out of the nozzle, which directly affects the amount of overspray.
- Nozzle Configuration. The type of nozzle used dictates the fan width, which in turn sets the optimum distance of the tip from the target surface. In our tests, we have experimented with 4/6/8/10" fan width tips. These tips also have varying orifice sizes, which dictates the volume of liquid that comes out of the nozzle.

In the first wall painting, the robot was moved at a speed of 60% with a pressure of 2000 psi, with the distance from the wall unmanaged. This resulted in a very thick coat of paint that stands out from the observable dripping down the wall.



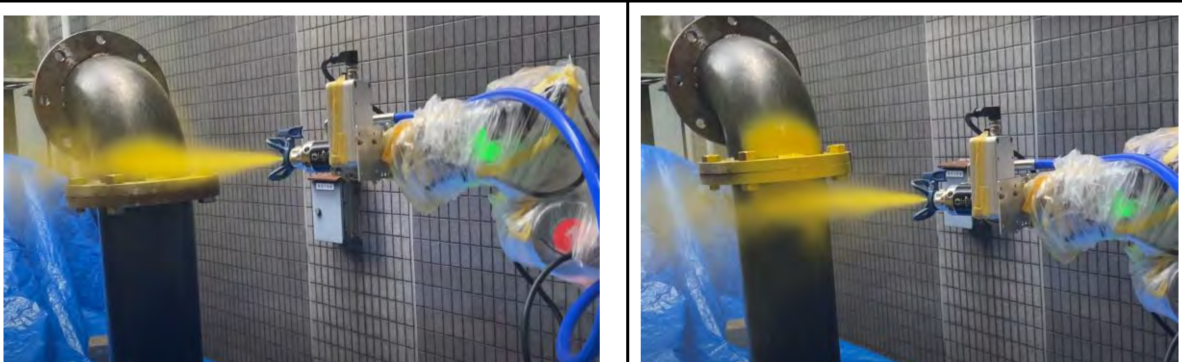
First attempt in wall painting using real paint, uncontrolled distance from wall uncontrolled
(pressure: 2000 psi, distance 6in, robot speed 60%)

Adjusting the distance to at least 10” from the wall, we get a finer layer of paint:



Wall painting with adjusted settings
(pressure: 1000 psi, distance 12in, robot speed 90%)

Similar tests have been done on a 6” pipe oriented vertically.

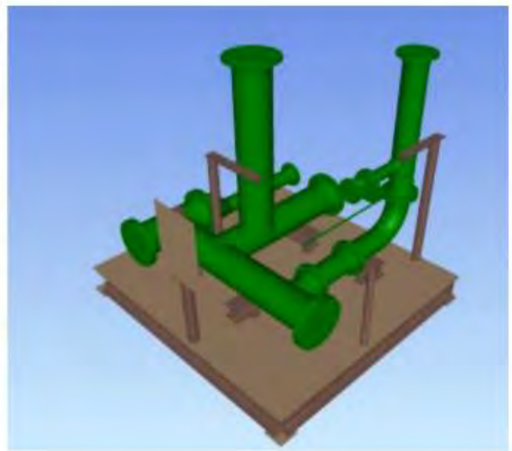


First attempt in pipe painting
(pressure: 1000 psi, distance 12in, robot speed 60%)

Pipe painting with adjusted settings
(pressure: 1000 psi, distance 12in, robot speed 90%)

SPRINT Robotics Painting Demo

The team also participated in the painting demonstration event hosted by SPRINT robotics which is sponsored by SHELL. We tested the capability of the arm on a real-world industrial painting scenario on a piping skid.



Notes on Finding the Optimal Parameters
The following heuristics are recommended when finding the optimal set of parameters for painting:

Robot speed	Tip speed should be at least 0.2m/s
Nozzle Selection	Select a fan width that matches the pipe diameter (ex. 10” fan width for a 10” pipe)
Distance	Spray from a distance equal to the fan width (ex. 10” distance for a nozzle with 10” fan width)
Pressure	Set to at least 1500KPa-2500KPa depending on thickness of the coating material
Spray Timing	Start the motion until it enters constant velocity mode; Stop the motion before it slows down until stop
Overlap	Maintain 50% overlap between sprays

Technical Limitations

Issue	Countermeasure
There is still a significant amount of **overblast** around the surface of the robot	As part of procedures, it is important to adjust the following operational “parameters”: **1. Type of paint and orifice size:** - Too big orifice for nonviscous paints like lightweight paints will cause more overblast than heavier liquids

	2. Pressure **3. Robot speed** - Finding the right robot speed applicable to the geometry of the surface
Too much paint applied on the surface	Similar to above, it is necessary to find the right combination of paint, orifice size, sprayer pressure, and speed to ensure that there is just the right amount of paint applied on the surface
Due to its length, the arm flexes during high-speed operation, creating oscillations at the tip that compromise its accuracy.	Several possible ways how to manage the oscillation of the arm at high-speeds, such as 1. Structural / Mechanical – increase the rigidity of the arm or revision in the geometry of the arm to dampen oscillation 2. Software Solution – improve the control algorithm to use smooth trajectories and maintain endpoint accuracy during hi-speed operation
Pre-planning the motion still takes a significant amount of operational time	More automation is necessary
Synchronizing the motion with the sprayer is currently manually triggered by the operator	Add a way to synchronize the spray action with the motion of the robot by software
Lack of emphasis on quantifying quality of work like measurement of DFT (dry film thickness), and production rate	Establish and monitor key performance indicators (KPIs) for quality (e.g., Dry Film Thickness) and productivity (e.g., production rate).

3.2. Mechanical design changes on the robot base to Improve Portability for FPSO application

To facilitate the use of Float Arms on Normally Unmanned Facilities and enhance robot portability, the robot's frame has been redesigned for modularity. This redesign aligns with common safety policies for these facilities, which limit single-operator lifts to a maximum of 20kg.

This is a continuation of the design, prototyping, assembly, and hardware validation that started during Phase II of the project.

The following were the key requirements identified for FPSO but also for onshore applications:

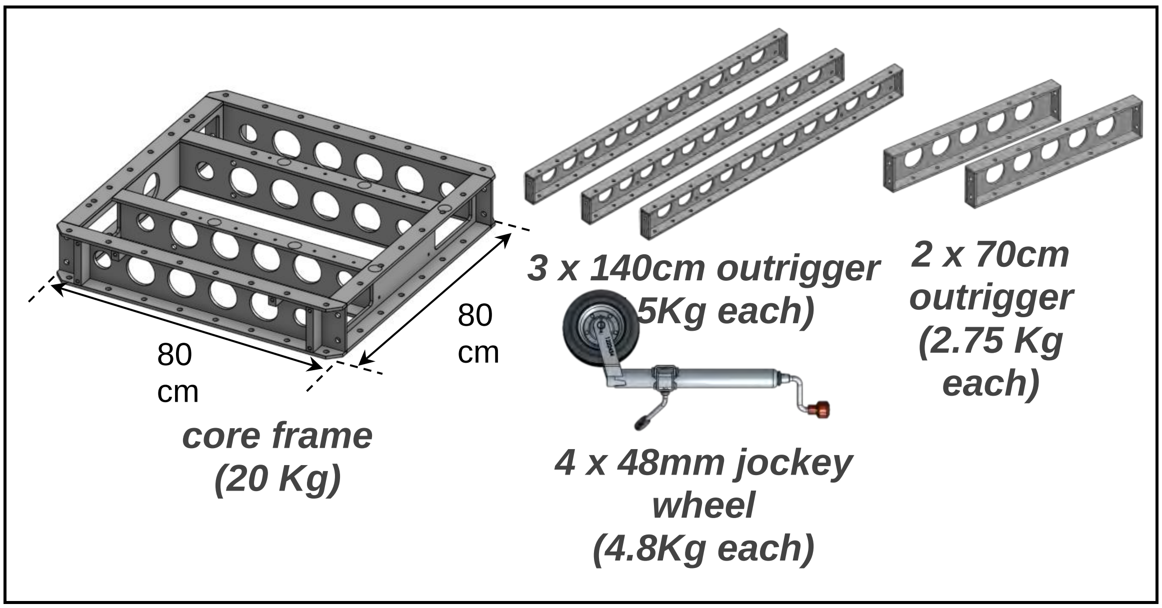
(1) Is configurable to support the weight of the whole arm at full extension without toppling over;
(2) Discrete components have to be at most 20Kg, light enough to be carried by one operator;
(3) Have built-in fork slots that would allow safe mounting on a forklift carrier, removing risk of toppling and turning;
(4) Have the option to attach casters, to allow the relocation of the robot from one point to another; but which the casters be removable in the case of setting the frame flat on the ground

3.2.1. Concept

Initially, the base frame was designed to split in half to allow for single-person transport due to lighter component weight. However, this presented challenges regarding the structural integrity of the adjoining clamps.

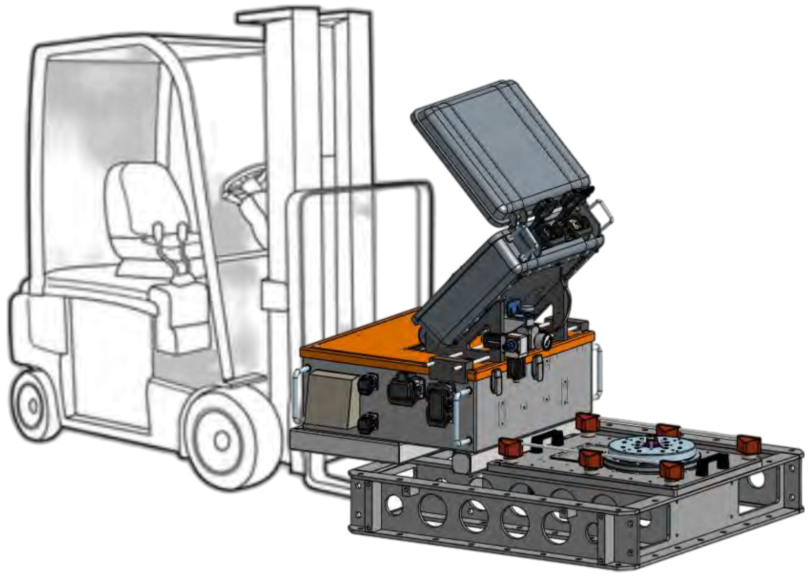
Consequently, a new approach was adopted. The frame is now divided into a core part, which bears the majority of mechanical stress, and add-on outriggers. This modular design offers flexibility in terms of both weight and functionality.

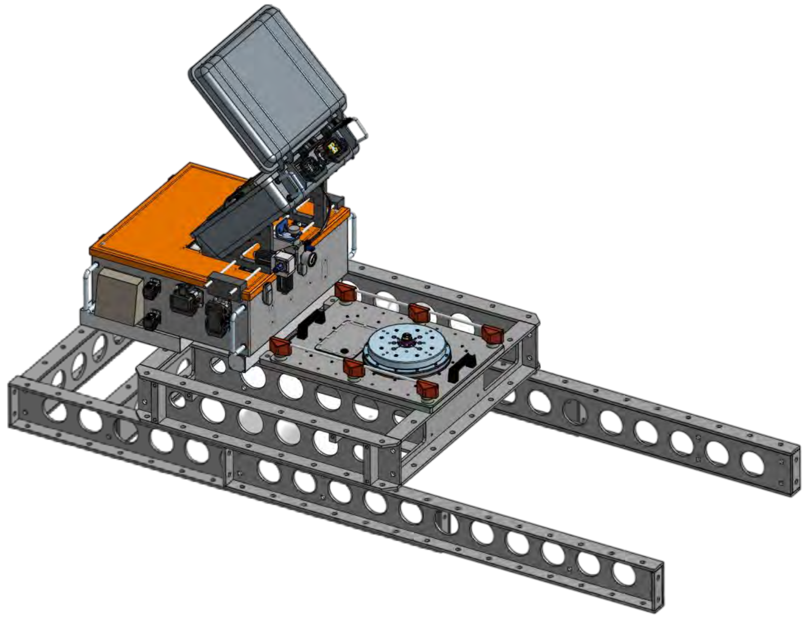
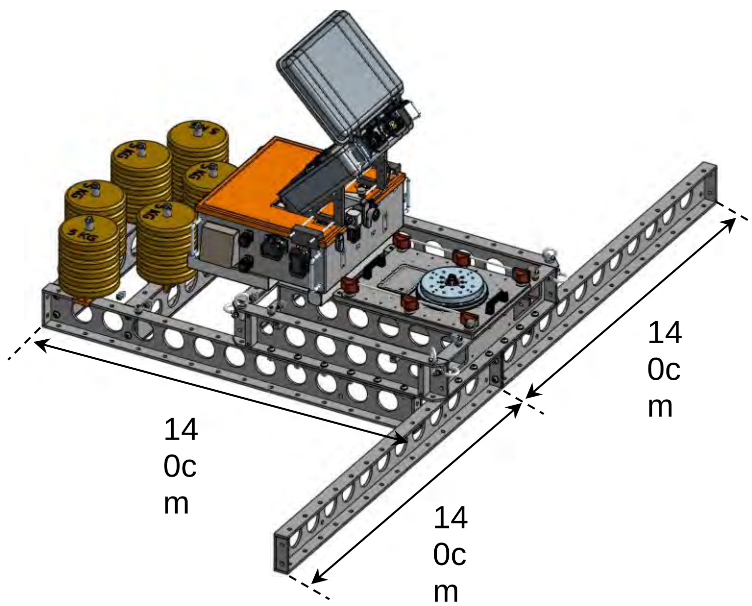
The base frame kit comprises the 20kg core, three 140cm outriggers, two 70cm outriggers, and four 48mm jockey wheels. This kit can be configured in numerous ways to suit various requirements, including arm extension direction, mounting conditions, and mobility needs. Such configurations must be pre-planned as part of the Job Safety Analysis (JSA) before any work commences.



3.2.2. Design Output

Shown below are some of many possible configurations depending on the use case:

Mounted on Lifter Possible Reach: ・**<0.5m** (horizontal) ・**5m** (vertical) ・**180°** work envelope (*1) (1) Check lifter configuration	
On wheels Possible Reach: ・**<0.5m** (horizontal) ・**5m** (vertical) ・**360°** work envelope (bottom-most link pointed vertically)	

On ground, front outrigger Possible Reach: • **2m** (horizontal) + 3m (with ballast) • **5m** (vertical) • **60°** work envelope	
On ground, full outrigger Possible Reach: • **7m** (horizontal) • **5m** (vertical) • **180°** work envelope	

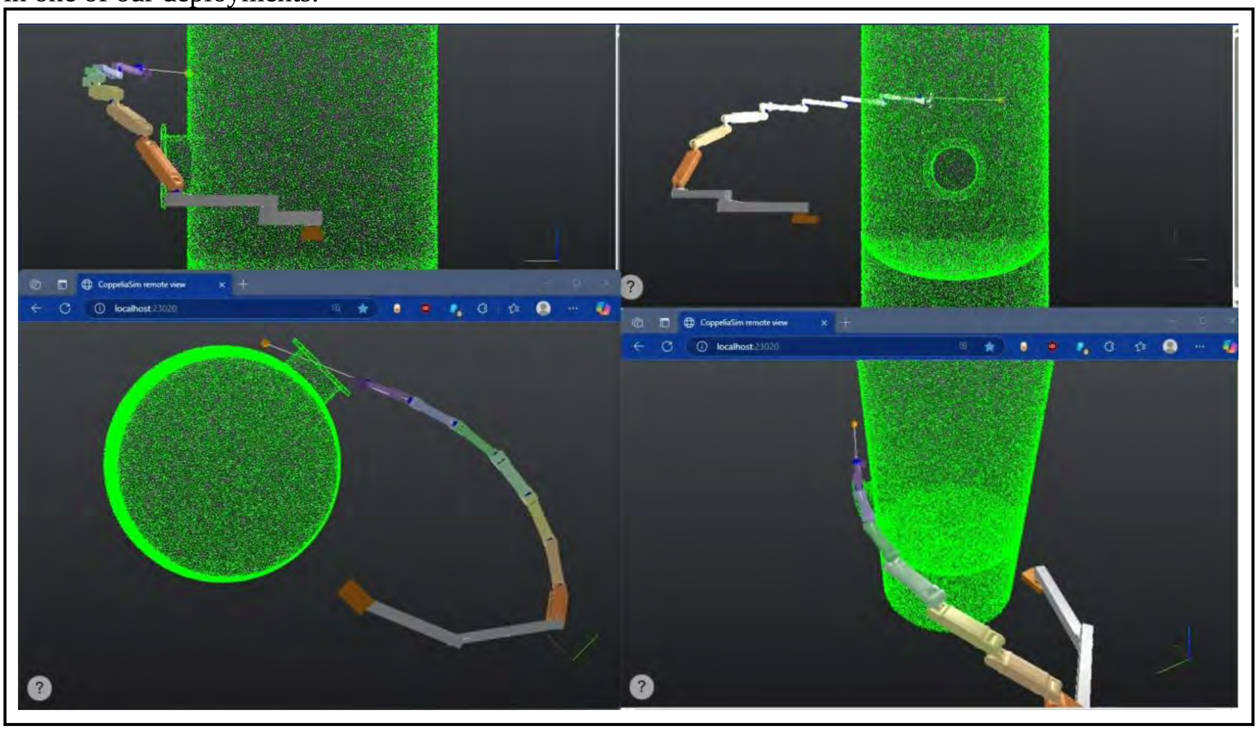
This base frame design is to be hardware validated on an FPSO at MODEC Singapore in November 2025.

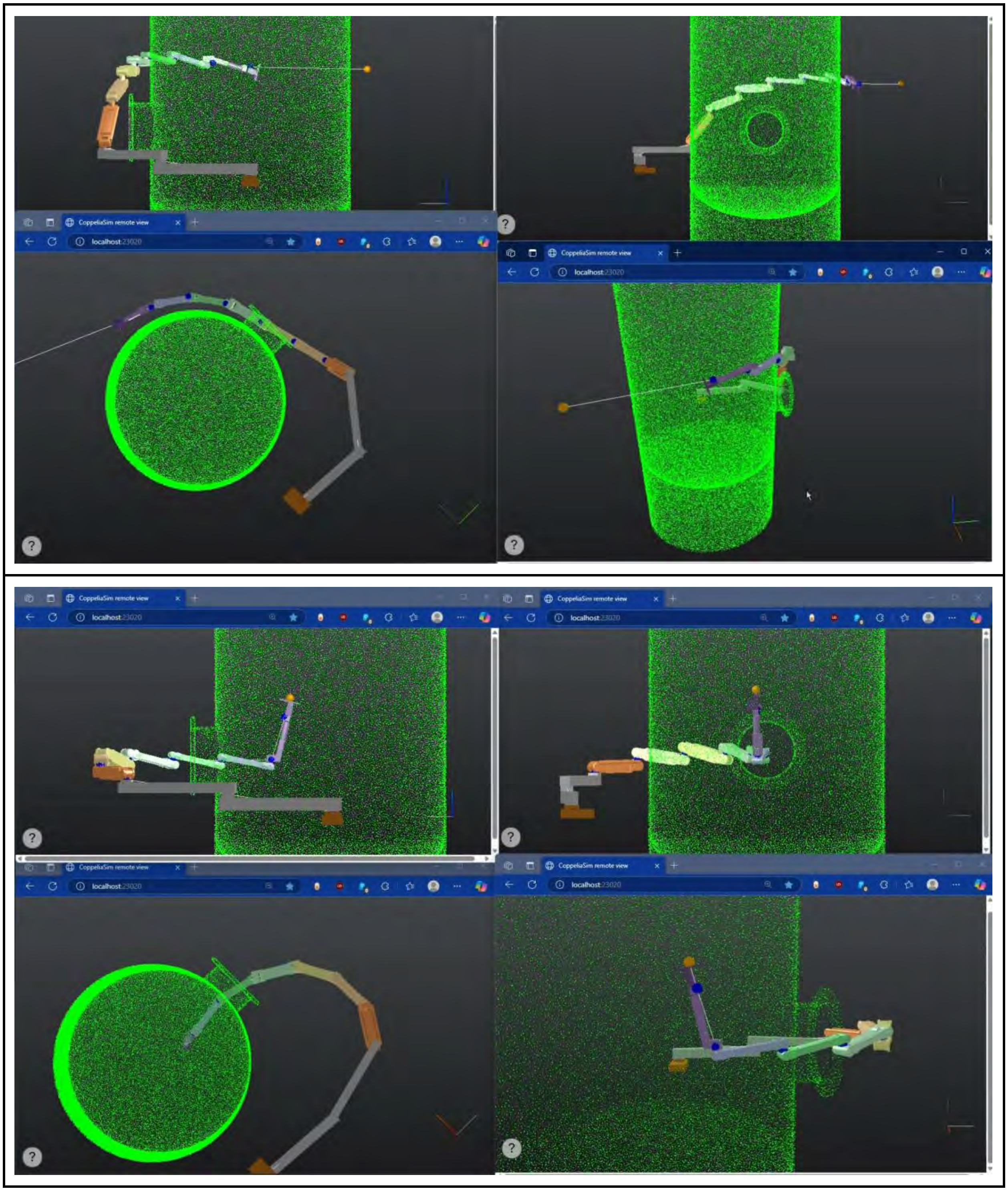
3.3. Software Improvement for Faster and Easier Arm Manipulability in Confined Spaces

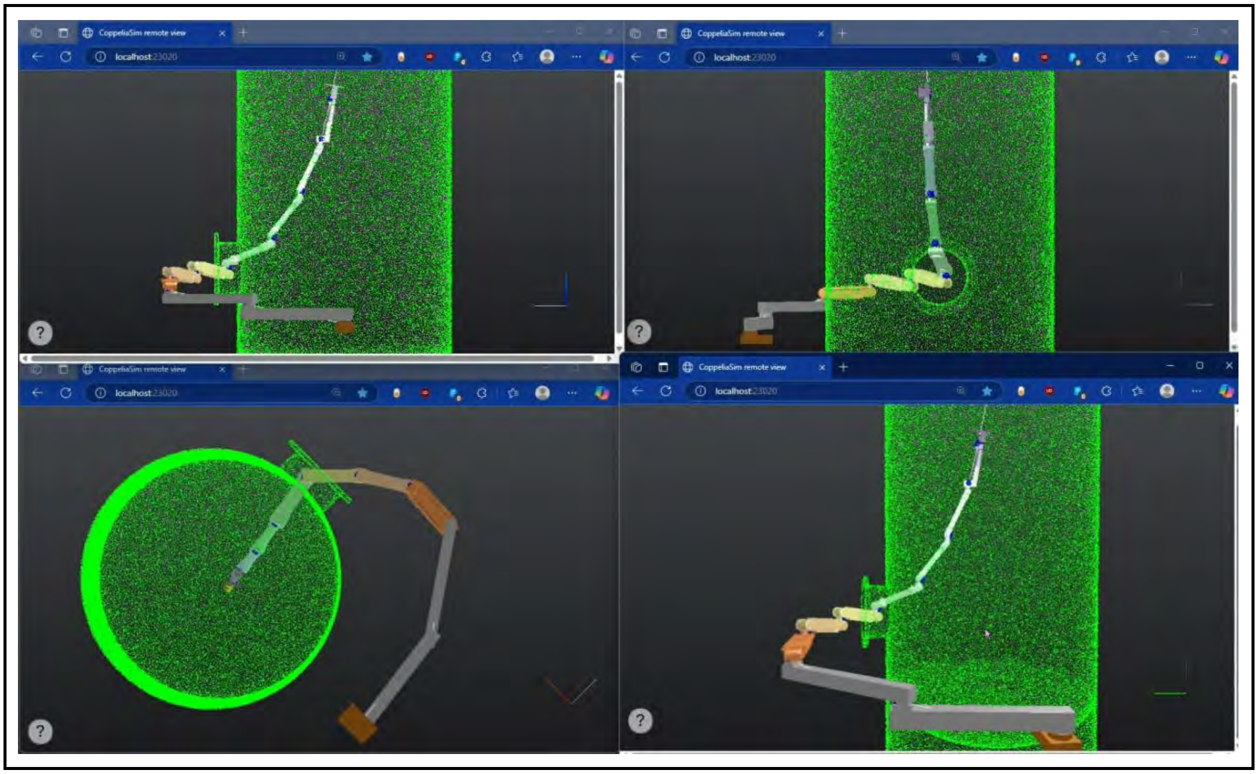
3.3.1. Development of a Snake-like motion software

In Phase 3, we present intuitive control. This will allow the end user to manipulate confined and tight spaces safely (go around a pressure vessel, go through a tight manhole) without having to rely on driving skills alone.

Shown below are some motion simulations using the new control algorithm integrated inside the Float Arm software. This asset is a point cloud generated from the 3D model of a storage tank from an actual refinery in one of our deployments.



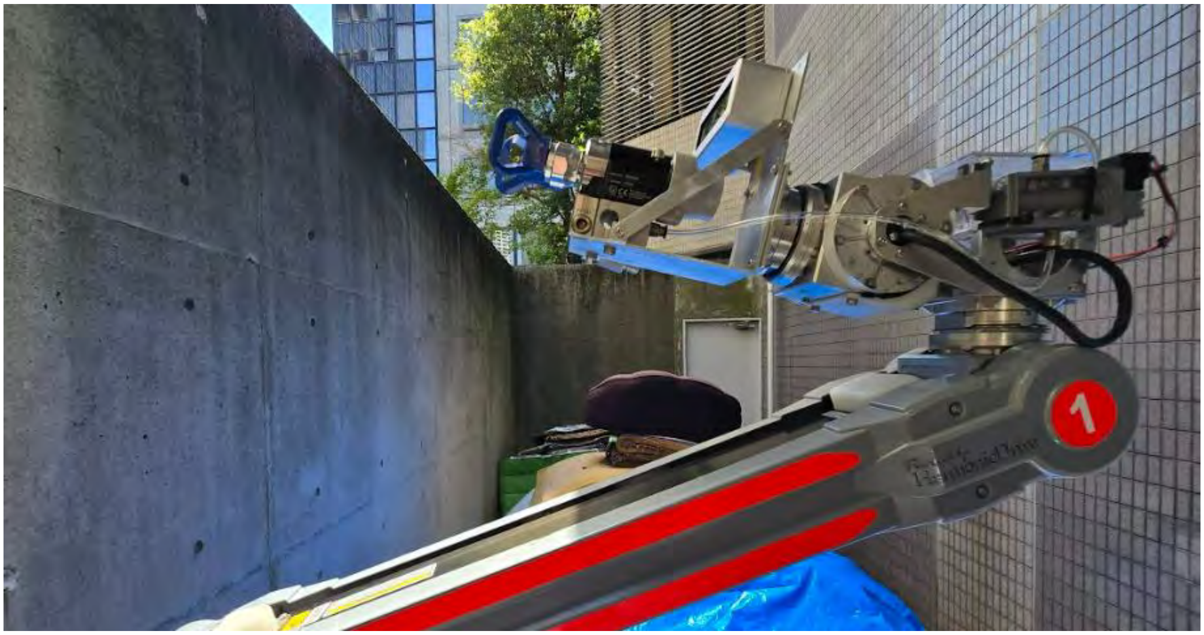

CoppeliaSim remote view
localhost:23020



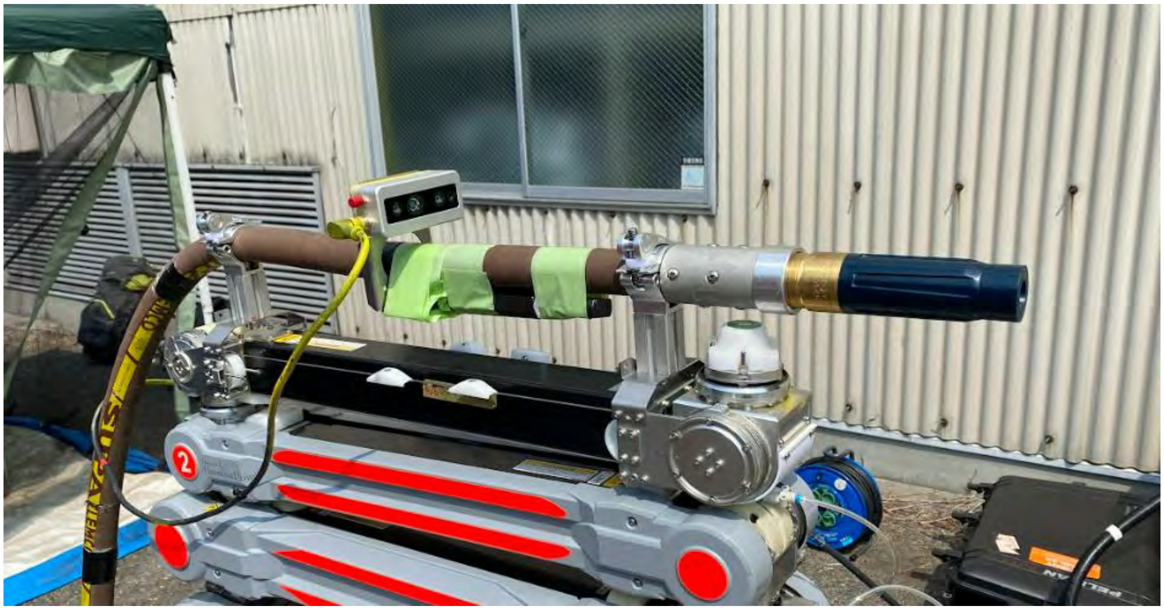
3.3.2. Installing of a Real-time 3D Depth Camera

The following is an image of the real-time 3d sensor that is evaluated to be attached at the tip of the end-effector. The sensor is compact at 112x47x38mm and 250g of weight and IP67 of enclosure. It provides a 87°x58° field of view depth, and has an optimal operating range of 30cm~3 meters. With the 30 frames per second depth streaming, it will provide the user a real-time feedback of the environment without having to stop and collect scans as per current method.

The 3D Depth camera was attached on the custom end-effectors used during the test of fabric maintenance tools.

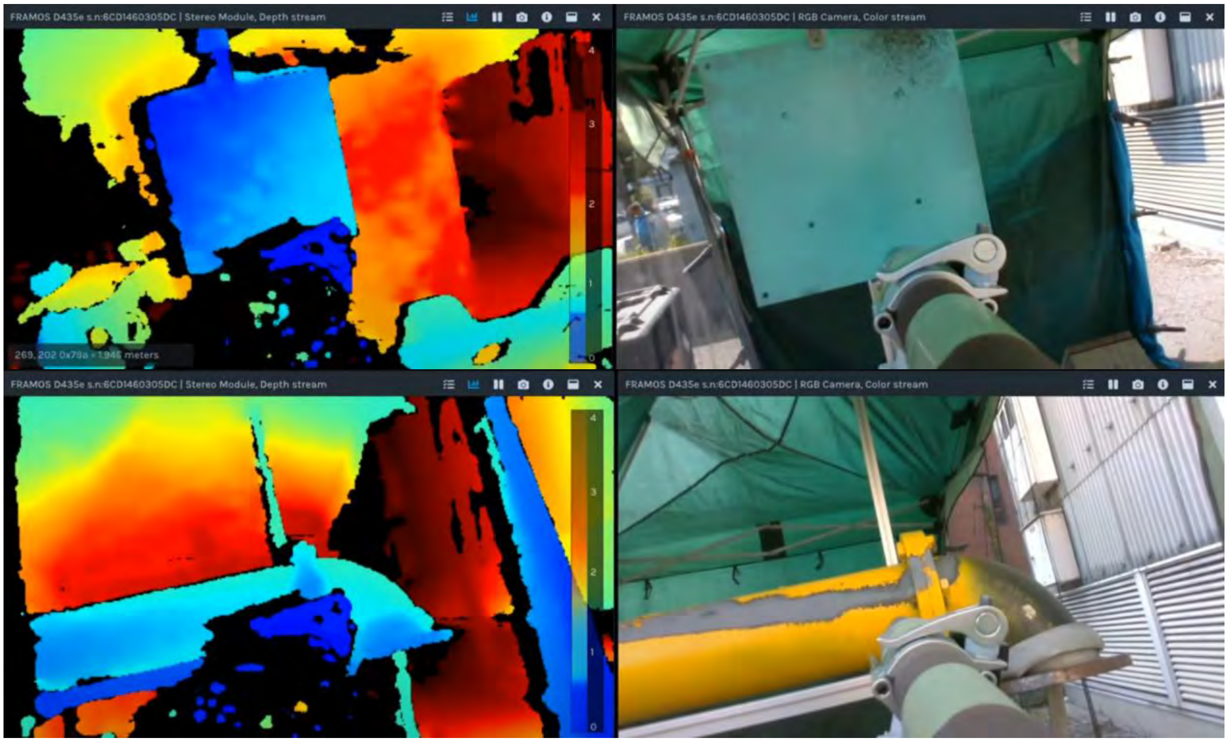


(a)

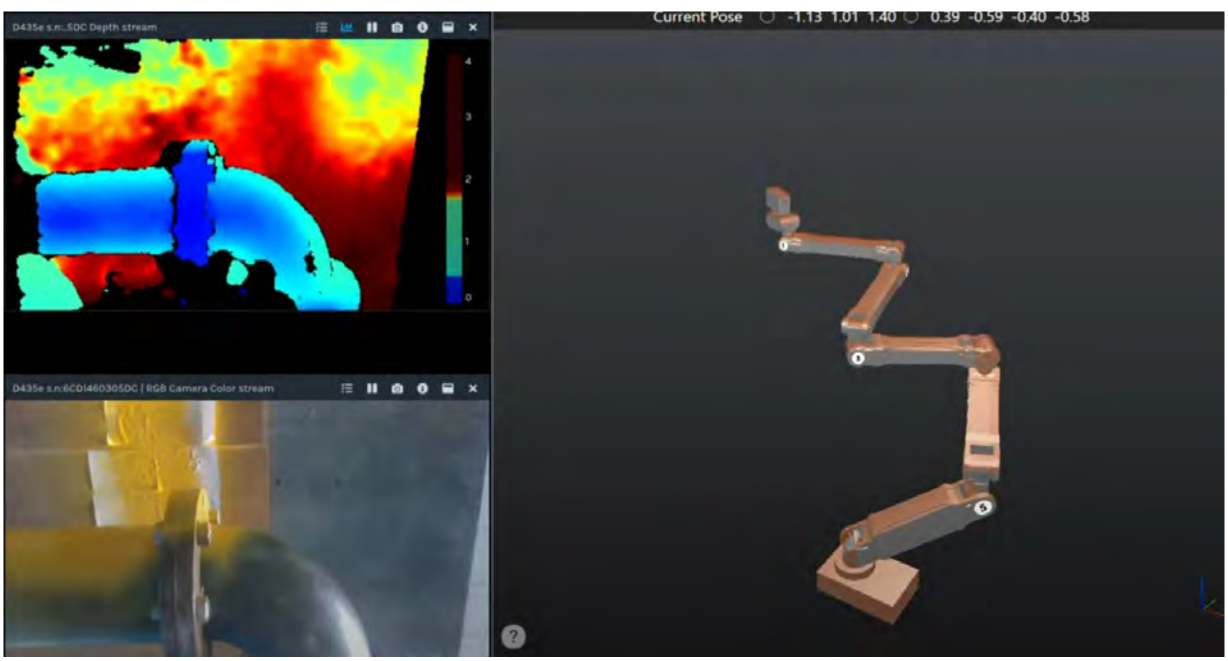


(b)

Mounting on the (a) coating end-effector, and (2) blasting hose for surface preparation



Operator view, blasting tip during surface preparation



Operator view, coating tip during painting

4. Conclusion and Future Work

This phase of work has confirmed the technical feasibility and industrial relevance of equipping the Float Arm with fabric maintenance capabilities, particularly in surface preparation and coating. The successful integration of sponge blasting and airless spraying tools, combined with outdoor validation trials, has demonstrated that robotic fabric maintenance can reduce human exposure while achieving results aligned with industry standards. At the same time, testing revealed clear opportunities for improvement, especially in managing thrust-induced loads and ensuring stable, precise motion under variable hose and nozzle conditions. These findings create a strong foundation on which to build the next stage of development.

Future investment will allow the project to expand in two critical directions.

On the application side, there is a need to diversify and industrialize the set of fabric maintenance tools supported by Float Arm. This includes:(1) refining hose routing, nozzle stabilization, and tool mounting concepts to enable reliable operations across more asset geometries and coating processes. Furthermore, we would like to extend the trials on using heavier coating medium such as zinc for rustproofing applications.

On the system side, (2) further research in motion control will directly improve robustness and usability. Advanced control strategies—such as semi-autonomous path planning, line tracing (following the path of the piping), etc.—offer the potential to expand operational limits, reduce operator workload, and ensure consistent results in demanding environments.

By advancing these two fronts together, the Float Arm can evolve from a proof-of-concept into a deployable robotic solution for surface preparation and coating in oil, gas, and chemical facilities. This direction not only supports safer, more efficient maintenance practices but also strengthens the case for wider industrial adoption. Continued funding will accelerate this trajectory, positioning the platform as a uniquely capable tool for addressing corrosion management, coating quality assurance, and long-reach maintenance challenges in complex facilities.